TFAWS Modeling Methods Paper Session

THERMAL & FLUIDS ANALYSIS WORKSHOP

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# Assessment of OpenFOAM CFD library for numerical simulations of shock turbulence interactions (STI)


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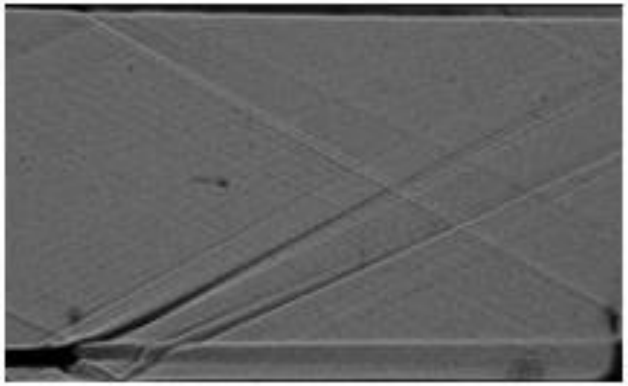
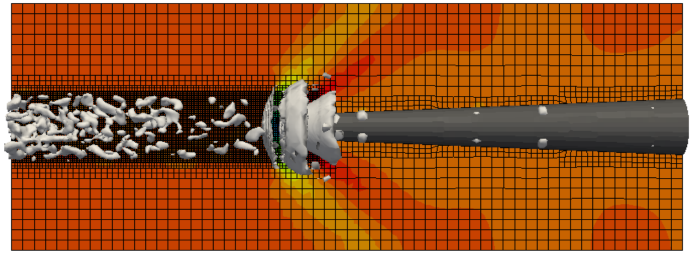
# Applications

- Supersonic film cooling for the J-2X nozzle extension
  - Large Eddy Simulations (LES) using OpenFOAM



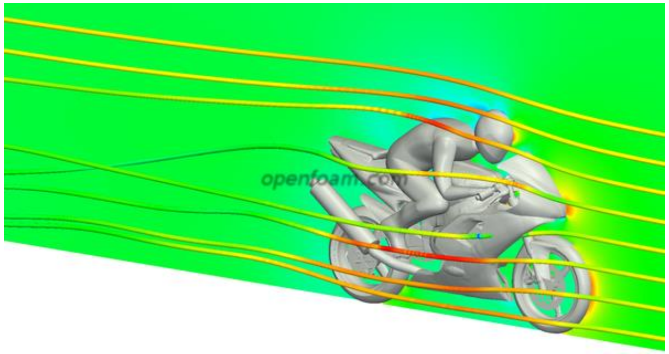
- Virtual probe
  - Build a transfer function connecting **measured fluctuations** with **upstream fluctuations**
  - With the help of LES (using OpenFOAM)



# Why OpenFOAM?

- Getting very popular in
  - Academia &
  - Industry

http://www.openfoam.com/



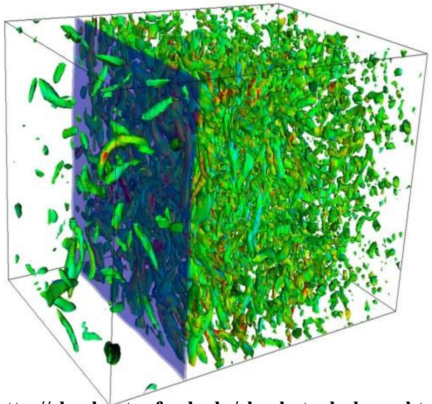
- Why?
  - Free
  - Open source
  - Easy to extend/develop
  - Several models for e.g., turbulence, combustion
  - Unstructured meshes
  - Scalability up to 1000s of CPUs

# Assessment – why?

- OpenFOAM already used for flows with **STI***** e.g.,
  - Vuorinen et al. (PoF, 25, 2013)

- But a systematic study of its efficacy is required
  - Similar to what Johnsen et al. (JCP, 229, 2010) did for high resolution DNS codes/methods

- Because **STI***** impose conflicting requirements on CFD codes
  - For resolving turbulence
    - Numerical dissipation should be **minimized**
  - For capturing shocks
    - Numerical dissipation should be **introduced**



http://shocks.stanford.edu/shock_turbulence.html

***** STI – shock turbulence interactions**

# Scope

- Evaluate different
  - **Solvers/approaches inside OpenFOAM**
  - Time stepping schemes
  - Limiters

# Solvers/approaches

- rhoCentralFoam – ***centralFoam***
  - **Ready made**
  - **No reported studies focused on STI*****
  - Central schemes e.g., Kurganov et al. (JCP, 160, 2001)
  - Relatively easy for polyhedral framework
  - Validation & verification, Greenshields et al. (IJNMF, 63, 2010)

- artificialViscosityFoam - ***artificialFoam***
  - **Already used e.g., Vuorinen et al. (PoF, 25, 2013)**
  - **Not ready made but fairly easy to code**
  - Cook et al. (JCP, 203, 2005) & Bhagatwala et. al (JCP, 228, 2009)

***** STI – shock turbulence interactions**

# Time stepping schemes

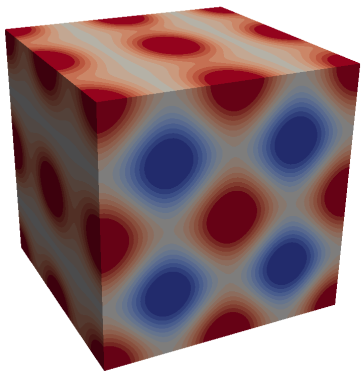
- Generally
  - Schemes like fourth order accurate Runge Kutta (**RK4**) are used in research
  - But codes like OpenFOAM, FLUENT don't offer those

- Schemes
  - Available
    - Implicit Euler (1$^{st}$ order)
    - OpenFOAM's "backward" (2$^{nd}$ Order)

  - Implemented
    - RK4 (4$^{th}$ order)

# Assessment – how?

- Suite of carefully chosen benchmark cases, Johnsen et al. (JCP, 229, 2010)
  - **3D Taylor-Green vortex**

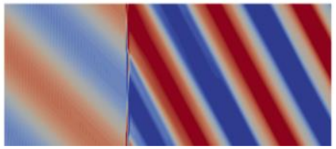


*p*

  - **Shu-Osher problem (1D)**

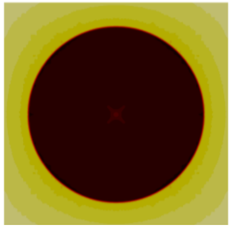
$\rho$

  - **Shock-vorticity/entropy wave interaction (2D)**



$\omega_3$

  - **Noh problem (3D)**



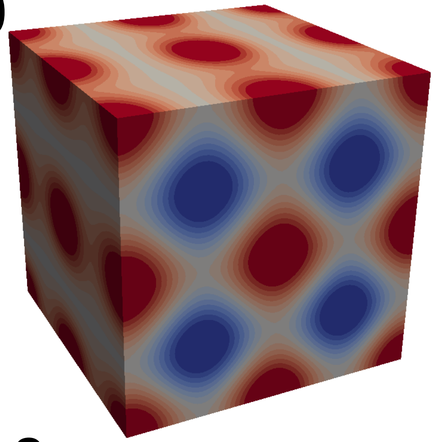
$\rho$

# 3D Taylor-Green vortex

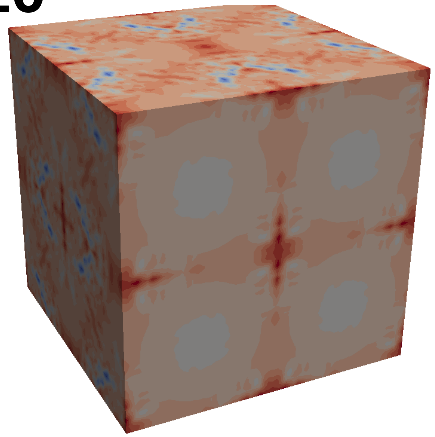
- Initial conditions

$$
\begin{aligned}
&\rho = 1,\\
&u_1 = \sin x_1 \cos x_2 \cos x_3,\\
&u_2 = -\cos x_1 \sin x_2 \cos x_3,\\
&u_3 = 0,\\
&p = 100 + \frac{[\cos(2x_3) + 2][\cos 2x_1 + \cos 2x_2] - 2}{16}
\end{aligned}
$$

***p* @ t=0**



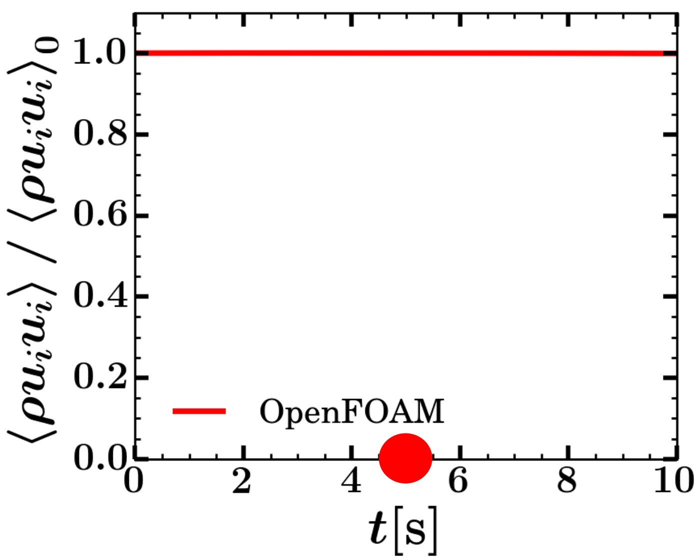
***p* @ t=10**



- Periodic boundary conditions
- Euler equations
- Well resolved at t=0
- t>0, vortex stretching, smaller scales
- Goals
  - Evaluate stability for severely under-resolved motions
  - Check measure of kinetic energy preservation

# 3D Taylor-Green vortex

- Verification
- Normalized kinetic energy evolution

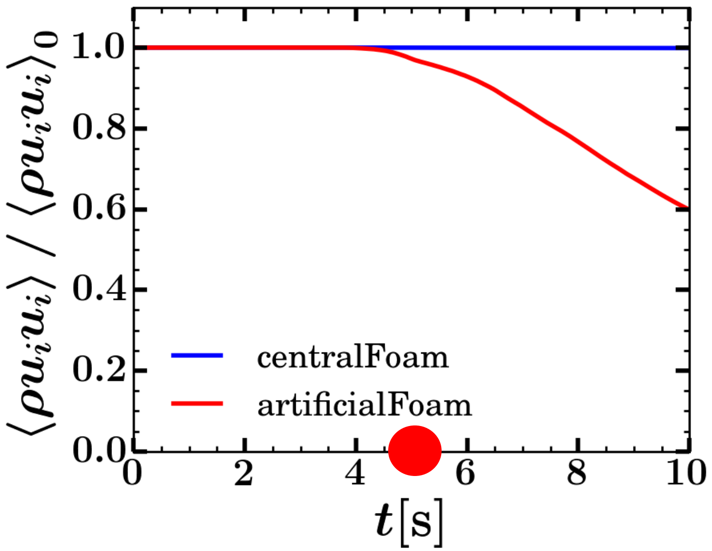



| Source | T-G energy t=5 |
|---|---|
| **Brachet et al. [1]** | **1** |
| Hybrid [2] | 1 |
| ADPDIS3D [2] | 0.998 |
| Stan [2] | 0.976 |
| Stan-I [2] | 0.976 |
| WENO [2] | 0.916 |
| **OpenFOAM** | **1** |


1. M.E. Brachet et al., J. Fluid Mech. 130 (1983) 411– 452
2. E. Johnsen et al., J. Comput. Phys. 229 (2010) 1213–37

# 3D Taylor-Green vortex

- Comparing solvers
- centralFoam preserves Kinetic Energy (KE) but artificialFoam does not

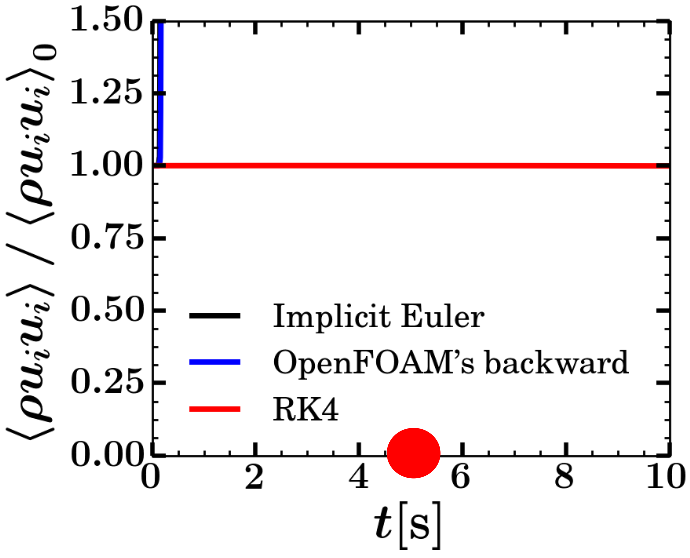



| Source | T-G energy t=5 |
|---|---|
| Brachet et al. [1] | 1 |
| centralFoam | 1 |
| artificialFoam | 0.972 |


1. M.E. Brachet et al., J. Fluid Mech. 130 (1983) 411– 452

# 3D Taylor-Green vortex

- Comparing time stepping schemes
- Solver crashes with Euler and backward schemes



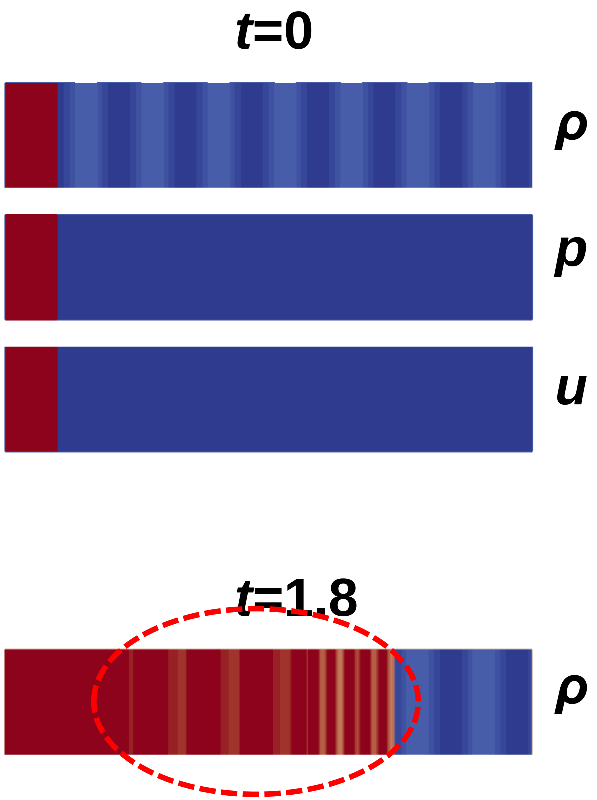

| Source | T-G energy t=5 |
|---|---|
| Brachet et al. [1] | 1 |
| Implicit Euler | - |
| OpenFOAM's backward | - |
| RK4 | 1 |


1. M.E. Brachet et al., J. Fluid Mech. 130 (1983) 411–452

# Shu-Osher problem (1D)

- Initial conditions

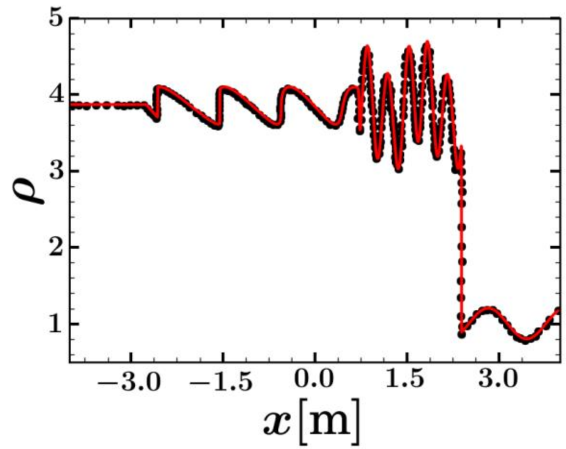
$$(\rho, \mathrm{u}, \mathrm{p}) = \begin{cases} (3.857143, 2.629369, 10.33333), & x < -4 \\ (1 + 0.2\sin(5\,\mathrm{x}), 0, 1), & x \geq -4 \end{cases}$$

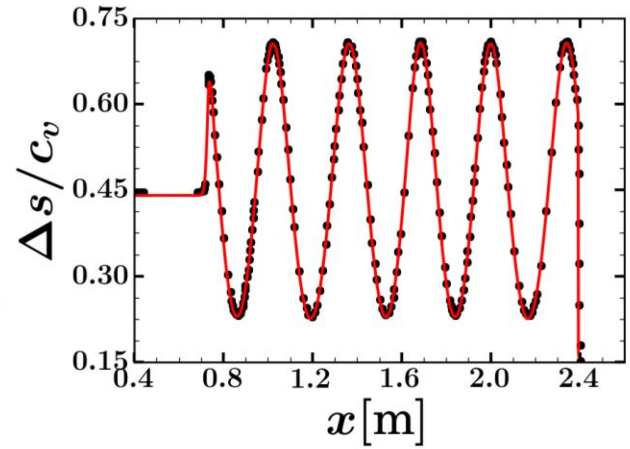


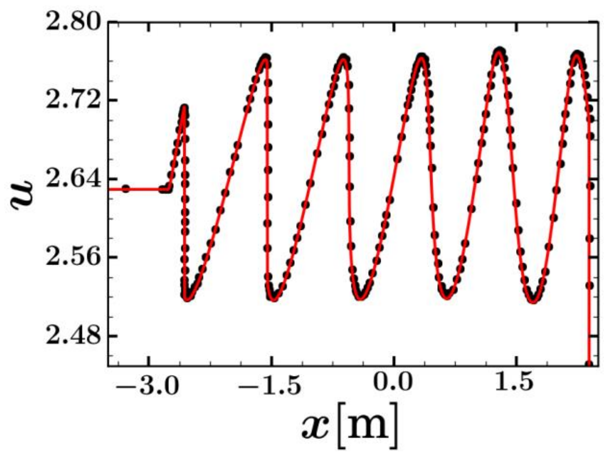

- Boundary conditions
  - Zero gradient
- Euler equations
- Goals
  - Evaluate ability to capture
    - a shock wave
    - its interaction with an unsteady density field
    - the waves propagating downstream of the shock

# Shu-Osher problem (1D)

- Verification

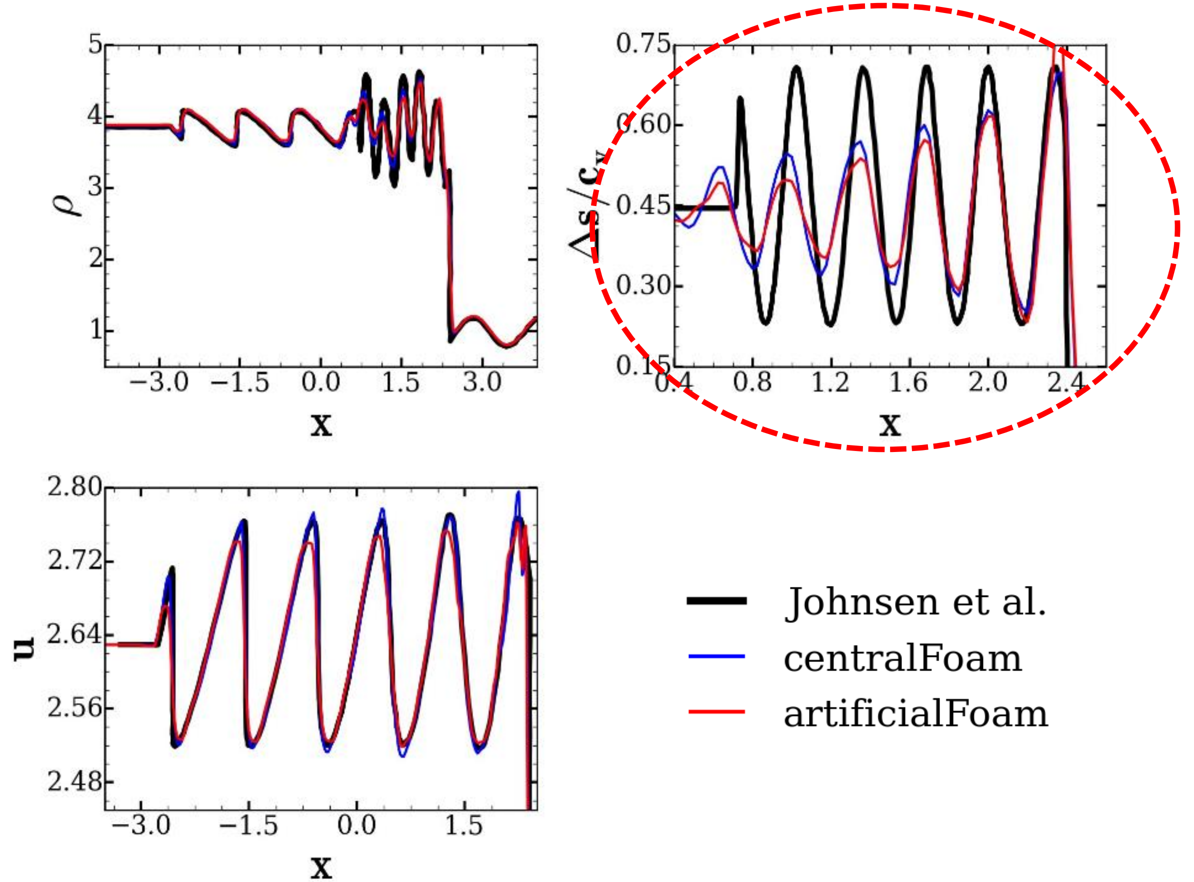


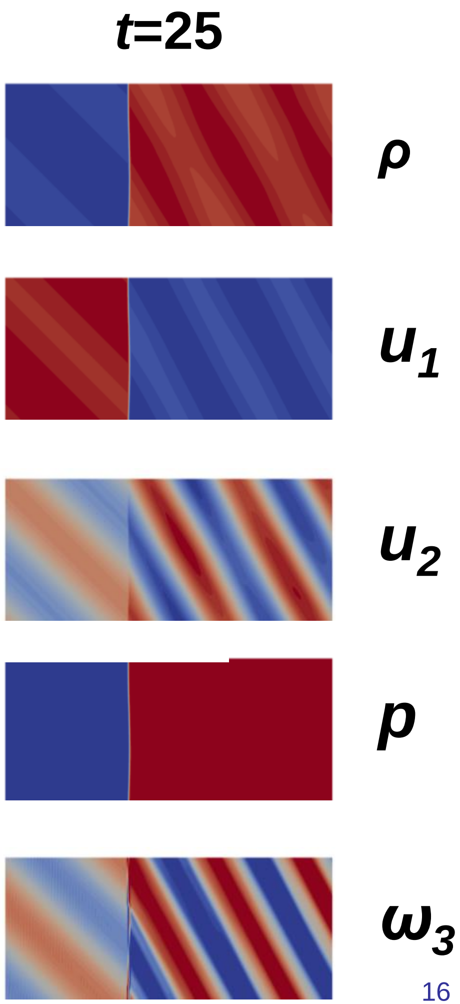

# Shu-Osher problem (1D)

- Comparing solvers on a coarse grid
- Again centralFoam performs better than artificialFoam



# Shock-vorticity/entropy wave interaction (2D)

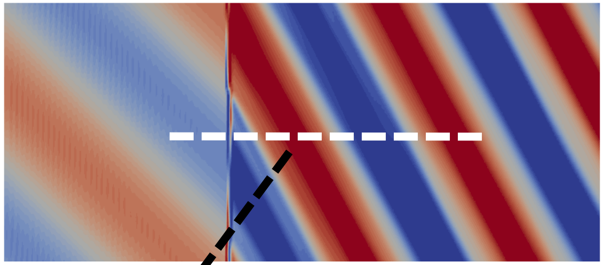
- Initial conditions
$$(\bar{\rho}, \bar{u}_1, \bar{p}) = \begin{cases} (\rho_L, u_L, p_L) = (1, 1.5, 0.714286), & x < 3\pi/2 \\ (\rho_R, u_R, p_R) = (1.862069, 0.8055556, 1.755952), & x \geq 3\pi/2 \end{cases}$$
$$\rho = \bar{\rho} + \rho_L A_e \cos(k_1 x_1 + k_2 x_2),$$
$$u_1 = \bar{u}_1 + u_L A_v \sin\psi \cos(k_1 x_1 + k_2 x_2),$$
$$u_2 = -u_L A_v \cos\psi \cos(k_1 x_1 + k_2 x_2),$$
$$p = \bar{p}$$
- Inflow boundary condition
$$\rho = \rho_L + \rho_L A_e \cos(k_2 x_2 - k_1 u_L t),$$
$$u_1 = u_L + u_L A_v \sin\psi \cos(k_2 x_2 - k_1 u_L t),$$
$$u_2 = -u_L A_v \cos\psi \cos(k_2 x_2 - k_1 u_L t),$$
$$p = p_L$$
- Euler equations
- Goals
  - Evaluate ability to capture
    - Shock-vorticity/entropy wave interaction

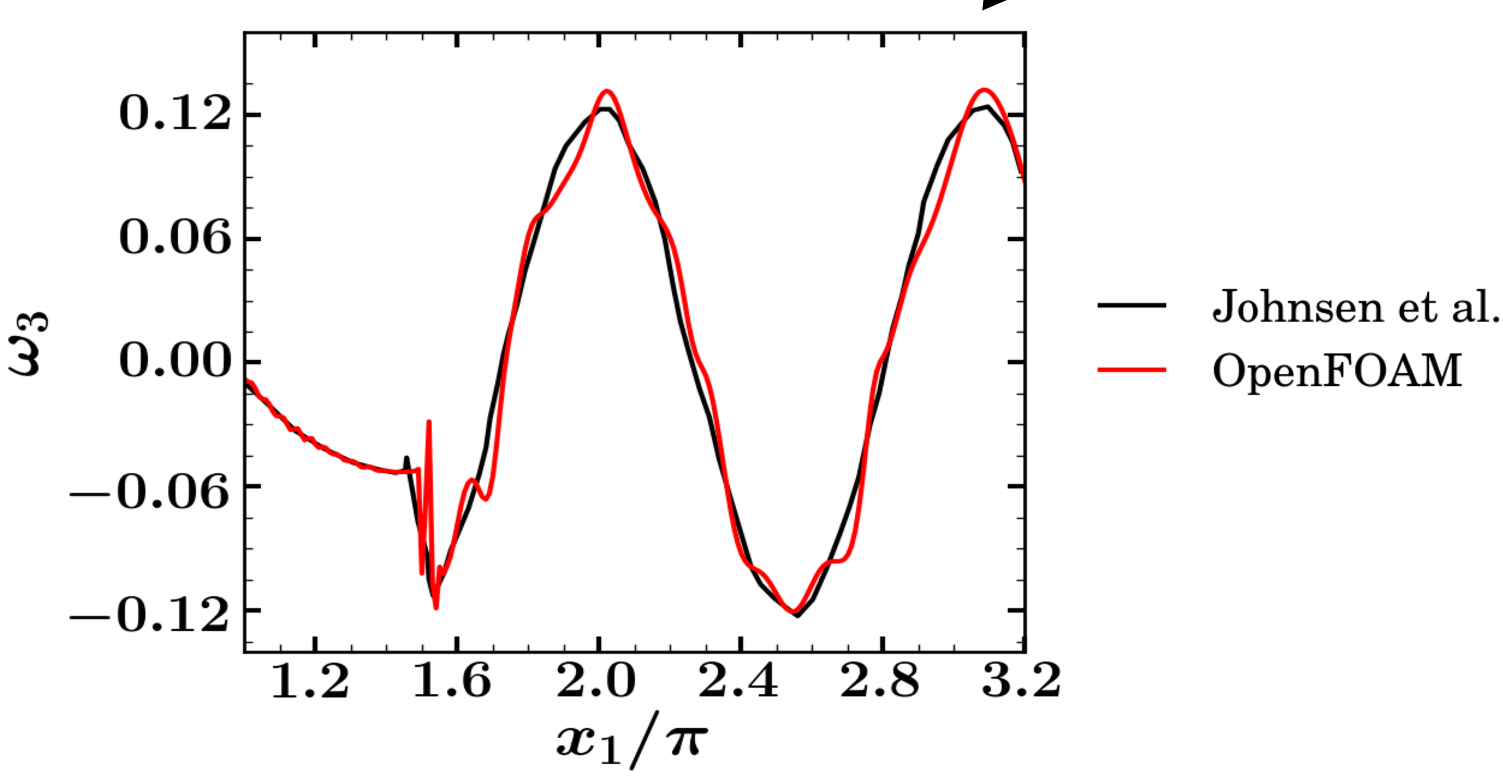


# Shock-vorticity/entropy wave interaction (2D)

- Verification
- $k_1 = \frac{k_2}{\tan\psi}, A_e = A_v = 0.025,$

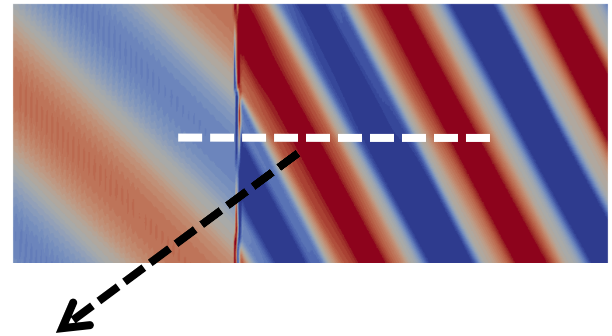
  $\psi = 45^o, k_2 = 1, t = 25$

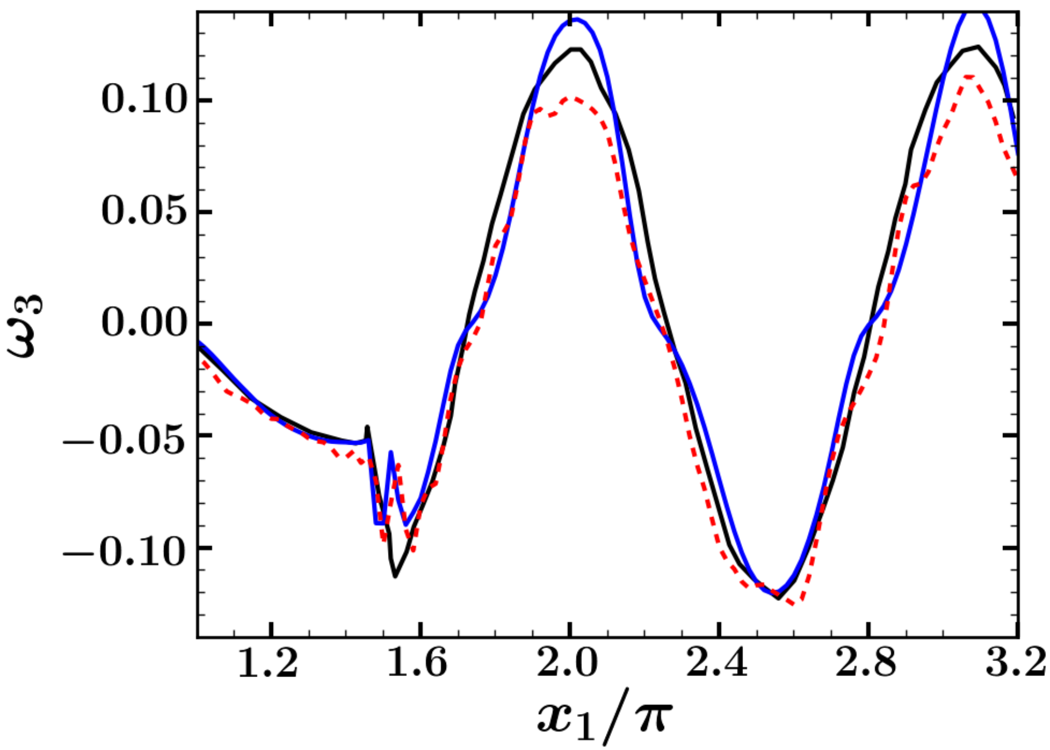




# Shock-vorticity/entropy wave interaction (2D)

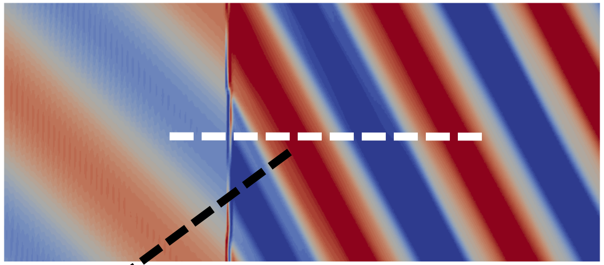
- Comparing solvers on a coarse grid
- centralFoam is better

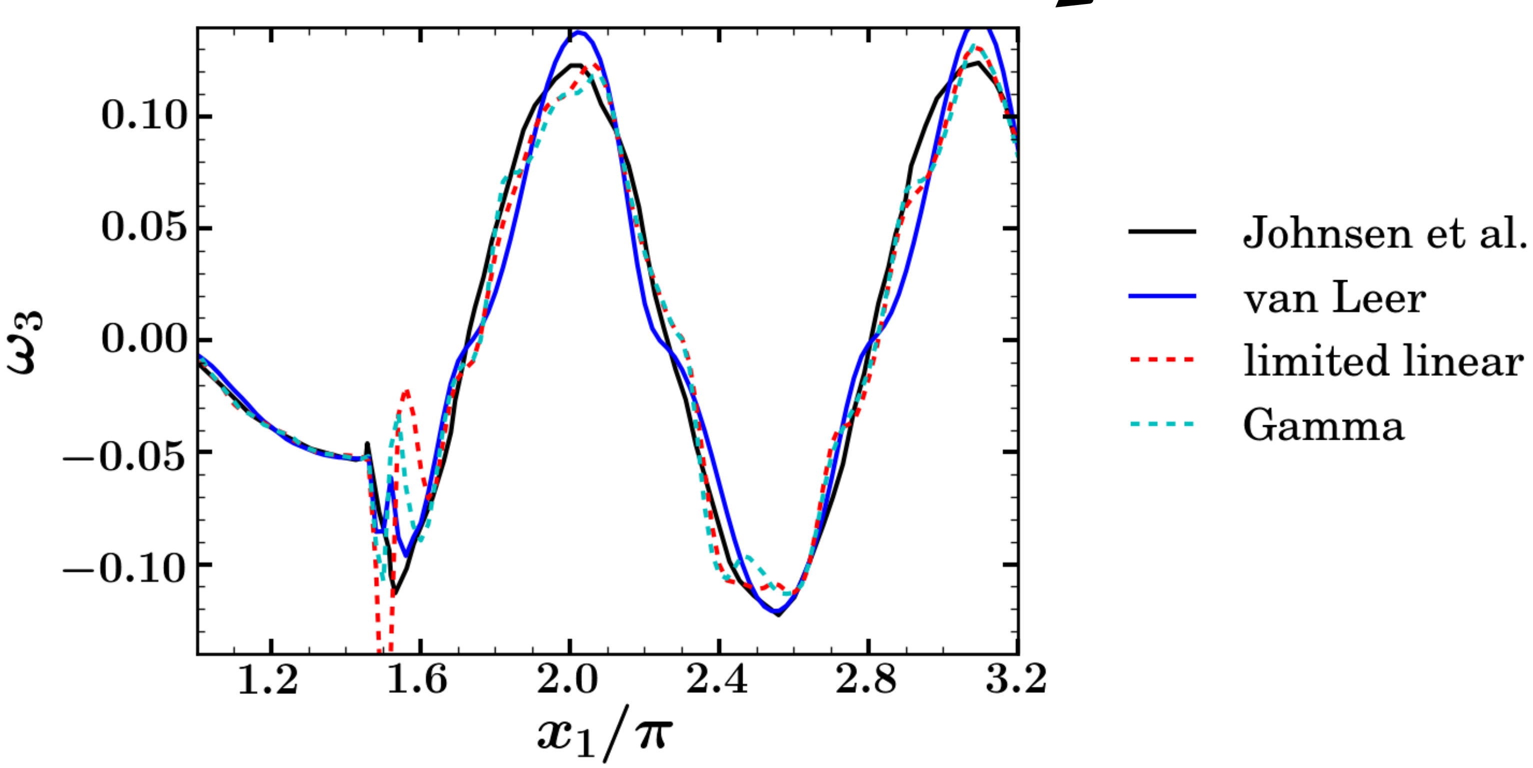




# Shock-vorticity/entropy wave interaction (2D)

- Comparing limiters on a coarse grid
- van Leer is better





# Noh problem (3D)

- Initial conditions (**ICs**)

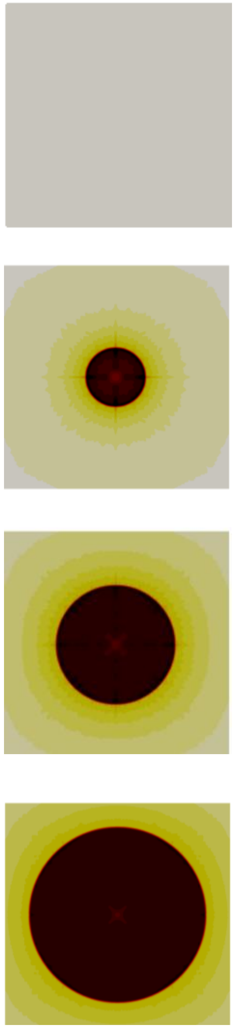
$$\rho = 1,$$
$$u_i = -x_i / r,$$
$$p = \varepsilon$$

- Analytical Solution (**AS**)

$$\rho = \begin{cases} 64, & r < t/3, \\ (1 + t/r)^2, & r \geq t/3 \end{cases}$$

- Boundary conditions, from ICs and AS
- Euler equations
- Goals
  - Evaluate ability to predict
    - Post-shock density
    - Shock speed
    - Spherical shape on a cartesian grid

***ρ***



***t*=0**

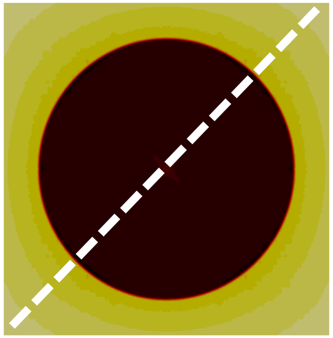
***t*=0.2**

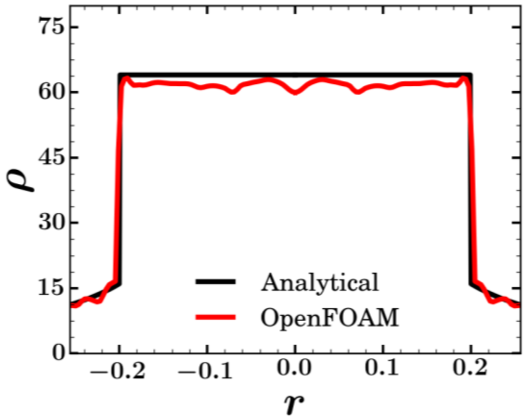
***t*=0.4**

***t*=0.6**

# Noh problem (3D)

- Verification
- centralFoam, RK4 and van Leer






| Source | $\rho_{mean}$ |
|---|---|
| **Exact** | **64.0** |
| Hybrid [1] | 63.2 |
| ADPDIS3D [1] | 63.3 |
| Stan [1] | 55.1 |
| Stan-I [1] | 54.9 |
| WENO [1] | 63.3 |
| **OpenFOAM** | **63.1** |

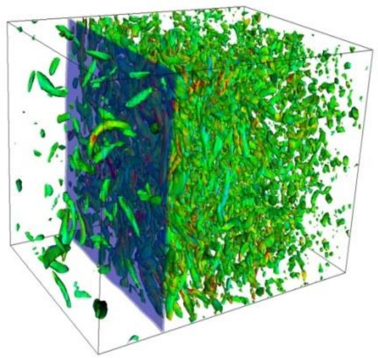

1. E. Johnsen et al., J. Comput. Phys. 229 (2010) 1213–37

# Concluding remarks

- Overall, OpenFOAM seems to be suitable for handling Shock Turbulence Interactions (STI)
  - centralFoam performs better than artificialFoam
  - Fourth order accurate Runge Kutta (RK4) time stepping scheme is more stable than the schemes offered by OpenFOAM
  - van Leer limiter provides best predictions

# Future work

- Compare performance on canonical shock-turbulence interaction case



- Compare the solvers in terms of computational cost

- Compare performance on unstructured grids
  - Tetrahedral
  - Polyhedral

- Evaluate recent artificial diffusivity based methods e.g., Guermond et al. (JCP, 230, 2011)

# Acknowledgements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- The authors are grateful to Dr. Ville Vuorinen (Aalto University, Finland) for useful discussions.

# Thank you; questions?